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MICROSTRIP NON-UNIFORM TRANSMISSION LINES TRIPLE BAND 3-WAY UNEQUAL SPLIT WILKINSON POWER DIVIDER

DERAR HAWATMEH[1], NIHAD DIB[1], KHAIR ALSHAMAILEH[2]

Key words: Power dividers, Wilkinson power dividers, Non-uniform transmission lines.

In this paper, we propose a non-uniform transmission lines (NTLs) 3-way triple band unequal split Wilkinson power divider (WPD). First, three impedance-varying transmission lines matched at 0.5, 1.25, and 2.0 GHz are designed in the even-mode analysis. Then, three NTL transformers are used to match the output ports to the 50 Ω connectors. Finally, the values of the isolation resistors (both in planar and non-planar configurations) are optimized to achieve an acceptable output ports matching and isolation at the desired frequency bands. To verify the underlined procedure, a triple band divider with power division ratios of 40 % at port 2 and 30 % at ports 3 and 4 is designed and simulated using two full-wave electromagnetic (EM) simulators. Simulation results show input/output ports matching and isolation less than –20 dB and transmission losses of –3.98 ± 0.5 dB and –5.23 ± 0.5 dB at the design frequencies.

1. INTRODUCTION

The need for feeding networks with arbitrary number of feeding lines and un-equal power division ratios motivated researchers to theorize and implement *N*-port microwave dividers. Among various dividers, the *N*-way Wilkinson power divider (WPD) received a noticeable interest in literature for its matched input/output ports and isolation levels. In [1], a general design procedure for *N*-way planar multi-frequency WPDs was presented, where the 2-way divider was considered as the key starting point in the design process. The divider consisted of multi-section transmission line transformers (TLT) and planar isolation resistors. The design of dual band equal split *N*-way WPDs was presented in [2, 3], where closed form design equations and genetic optimization were adopted to calculate the different design parameters. An unequal split dual band planar *N*-way WPD was proposed in [4] by combining two-section dual frequency transformers. Also, a quad band design approach was presented in [5], where a new algorithm to design quad band WPD, by transforming the dual band artificial transmission line into a quad band one, was proposed. The simulated data, carried out using "Ansoft Designer" simulator, validated the design approach. To overcome the narrow bandwidth drawback of the proposed design, more cells/stages were needed, which increased the design overall size.

However, the aforementioned approaches main drawback is the large circuit they occupy, especially with multi-section multi-frequency designs. To overcome the resulting large circuit area of the *N*-way power divider, various miniaturization techniques were investigated (*e.g.*, non-uniform transmission lines (NTLs), stubs, stepped impedance structures) [6–17].

In this paper, we propose a systematic approach to design unequal split *N*-way WPDs with reduced size and multi-frequency operation utilizing the concept of impedance-varying (non-uniform) transmission lines, where the three bands operation is achieved using only one section of the non-uniform transmission lines, unlike the multi-section approach, where the number of sections is a function of the bands number. Furthermore, employing the NTLs enhances the power divider performance at frequencies other than the design frequencies in addition to suppressing/partially-suppressing the odd harmonic as proved in our previous work [10]. This paper is organized as follows: Section 2 discusses the general design steps; Section 3 provides an example of a 4:3:3 3-way triple band WPD and discusses the theoretical and simulated results. Finally, conclusions and remarks are drawn in Section 4.

2. DESIGN PROCEDURE

Figure 1(a) illustrates the conventional layout of a single frequency non-planar unequal split 3-way WPD, where Z_{02}, Z_{03}, and Z_{04} are the characteristic impedances of the three uniform arms, and k_n^2 ($n = 1, 2, 3$) are the power splitting ratio constants (defined below). Figure 1b represents the proposed 3-way unequal split NTL-based triple frequency divider, in which each NTL arm has a varying characteristic impedance of $Z(z)$.

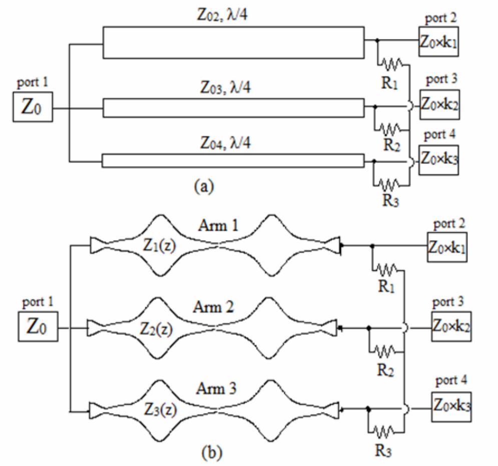


Fig. 1 – The layout of the 3-way non-planar unequal split WPD: a) conventional; b) NTL-based.

The characteristic impedances of the three main arms in the conventional design as well as the power splitting ratio constants can be found using the analysis presented in [1, 16].

[1] Jordan University of Science and Technology, Department of Electrical Engineering, P. O. Box 3030, Irbid 22110, Jordan, E-mail: dfh_ee@hotmail.com, nihad@just.edu.jo
[2] Purdue University Northwest, Electrical and Computer Engineering Department, Hammond Campus 2200, 169th Street, Hammond, IN 46323, E-mail: kalshama@pnw.edu

First, to find Z_{02}, output ports 3 and 4 are combined together to form a 2-way WPD with port 2 as the first output port, and $P'=P_3+P_4$ as the second output port, with a power ratio constant of $k_1^2=(P_3+P_4)/P_2$. Second, to find Z_{03}, ports 2 and 4 are combined together forming another 2-way WPD, with port 3 as the first output port, and $P''=P_2+P_4$ as the second output port, with a power ratio constant of $k_2^2=(P_2+P_4)/P_3$. Finally, Z_{04} can be found by combining ports 2 and 3 resulting in a 2-way WPD with port 4 as the first output port, and $P'''=P_2+P_3$ as the second output port, with a power ratio constant of $k_3^2=(P_2+P_3)/P_4$. Based on the above analysis, the characteristic impedances Z_{02}, Z_{03}, and Z_{04} are found using the following equations [18]:

$$Z_{02}=Z_0\sqrt{k_1\times\left(1+k_1^2\right)} \tag{1.a}$$

$$Z_{03}=Z_0\sqrt{k_2\times\left(1+k_2^2\right)} \tag{1.b}$$

$$Z_{04}=Z_0\sqrt{k_3\times\left(1+k_3^2\right)} \tag{1.c}$$

Using the even-mode analysis presented in [18], the output port of the M^{th} arm is matched as shown in Fig. 2(a). The M^{th} arm here (M^{th} arm of the N-way WPD) represents the first arm of the two ports WPD, in which its characteristic impedance needs to be calculated, and the other output ports are combined as discussed above. As an example, to design the first arm of the 3-way WPD adopting the two ports analysis, Z_{02} can be found using equation (1.a). Hence, the arm will be matched to a source impedance of $Z_0\times(1+K_1^2)$, and a load impedance of $Z_0\times K_1$ as described in [18], while the second and the third arms combination represents the second arm of the two ports WPD. Also, to design the second arm ($M = 2$) of the 3-way WPD, Z_{03} is the characteristic impedance of the first arm of the two ports WPD, which is matched to a source impedance of $Z_0\times(1+K_2^2)$, and load impedance of $Z_0\times K_2$, while the second arm of the 2-way WPD is the combination of the first arm and third arm of the 3-way WPD.

In order to design the proposed NTL-based WPD, each arm of the conventional design is replaced with its equivalent NTL that operates at three frequencies [19]. Each NTL has varying characteristic impedance $Z_M(z)$ and phase constant $\beta_M(z)$, as opposed to the conventional uniform transmission line that has a constant characteristic impedance Z_{0M} and phase constant β_{0M}. The design of each NTL starts by subdividing it into uniform electrically short sections, and the overall ABCD matrix of the whole NTL can be obtained by multiplying the ABCD matrices of such sections. Then, for each NTL, the following truncated Fourier series expansion for the normalized characteristic impedance $\overline{Z}_M(z)=\overline{Z}_M(z)/Z_0$ is considered:

$$\ln\left(\overline{Z}_M(z)\right)=\sum_{n=0}^{N}F_n\cos\left(\frac{2\pi nz}{d}\right). \tag{2}$$

Figure 2b shows the even mode circuit, where the NTLs are designed to have input reflection coefficients $\left|\Gamma_{in}\right|$ equal to zero (or very small) at the design frequencies.

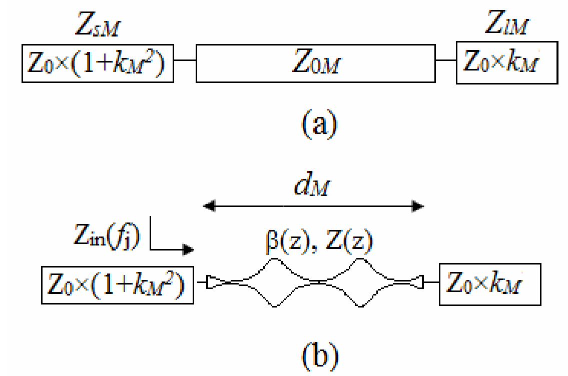


Fig. 2 – Even-mode analysis of the M^{th} arm, where $M = 1, 2, 3$: a) uniform arm; b) NTL-based arm.

The following error function, written in terms of $\left|\Gamma_{in}\right|$ at N design frequencies f_j ($j = 1, \ldots, N$), is used [20]:

$$\text{Error}_{input}=\sqrt{\sum_{j=0}^{N}\left|\Gamma_{in}\left(f_j\right)\right|^2}, \tag{3}$$

where

$$\Gamma_{in}\left(f_j\right)=\frac{Z_{in}\left(f_j\right)-Z_s}{Z_{in}\left(f_j\right)+Z_s} \tag{4}$$

where Z_S is the source impedance expressed by $Z_0(1+k_M^2)$ as shown in Fig. 2. It is worth mentioning here that the error function in (3) should be restricted by some constraints, such as reasonable fabrication and physical matching, as follows [20]:

$$\overline{Z}_{\min}\le\overline{Z}(z)\le\overline{Z}_{\max} \tag{5.a}$$

$$\overline{Z}(0)=\overline{Z}(d)=1. \tag{5.b}$$

This constrained non-linear optimization problem is solved using the built-in Matlab "fmincon" routine. The isolation resistors values are found using the optimization engine of Ansoft Designer Simulator [21].

3. EXAMPLE

A 3-way unequal split triple-band NTL-based WPD with power splitting ratios of 40 % for port 2 and 30 % for each of ports 3 and 4 ($k_1^2=1.5$, and $k_2^2=k_3^2=2.333$) is designed to operate at 0.5, 1.25, and 2.0 GHz. Considering a reference impedance of 50 Ω, using (1), the impedances of the conventional WPD arms are found to be: Z_{02} = 87.5 Ω, and $Z_{03}=Z_{04}$ = 112.83 Ω. Using the even mode analysis, the source and load impedances for the main arms are Z_{s1} = 125 Ω, Z_{l1} = 61.23 Ω, $Z_{s2}=Z_{s3}$ = 166.67 Ω, and $Z_{l2}=Z_{l3}$ = 76.38 Ω. A flame retardant type 4 (FR4) substrate with ε_r = 4.6, loss tangent of 0.02, and thickness of 1.6 mm is used. The length of each NTL arm is chosen to be 85 mm (approximately λ / 4 at the lowest frequency).

Figure 3 shows the layout of the designed WPD with extra three NTL transformers for output ports' matching purposes. The matching transformers' characteristic impedances are: ZT1 = √(50×61.24) = 55.33 Ω, ZT2 =' = √(50 × 76.38) = 61.8 Ω, and ZT3 = √(50 × 76.38) = 61.8 Ω, each with a length of 82 mm.

The parameters needed for the optimization process are shown in Table 1. The optimized Fourier coefficients are shown in Table 2 for each arm and matching transformer. Three resistors are used to achieve an acceptable isolation between the output ports. The values of these isolation resistors are found to be: R1 = 54 Ω, R2 = 60 Ω, and R3 = 62 Ω. The designed three-way, NTL-based WPD is simulated using the method of moments-based IE3D [22] and the finite element method-based high frequency structure simulation (HFSS) [23]. The simulated S-parameters are shown in Fig. 4.

Table 1

Parameters of the uniform lines
and equivalent NTLs needed for optimization

	UTL	NTL	Constraints
WPD Section 1	Z_0= 87.5 Ω	K = 50 d_1 = 84 mm	at 0.3 mm Z_0= 128.53 Ω $\rightarrow \bar{Z}_0 = 1.469$ at 15 mm Z_0= 15.288 Ω $\rightarrow \bar{Z}_0 = 0.145$
WPD Section 2 Section 3	Z_0= 112.83 Ω	K = 50 d_2 = 84 mm	at 0.3 mm Z_0= 128.53 Ω $\rightarrow \bar{Z}_0 = 1.14$ at 15 mm Z_0= 15.288 Ω $\rightarrow \bar{Z}_0 = 0.1355$
55.344 Ω transformer	Z_0= 55.344 Ω	K = 50 d_{T1} = 81 mm	at 0.3 mm Z_0= 128.53 Ω $\rightarrow \bar{Z}_0 = 2.322$ at 15 mm Z_0= 15.288 Ω $\rightarrow \bar{Z}_0 = 0.276$
61.8 Ω transformers	Z_0= 61.8 Ω	K = 50 d_{T2} = d_{T3} = 84 mm	at 0.3 mm Z_0= 128.53 Ω $\rightarrow \bar{Z}_0 = 2.08$ at 15 mm Z_0= 15.288 Ω $\rightarrow \bar{Z}_0 = 0.247$

Table 2

The optimized Fourier coefficients
for each arm and matching transformers

87.5 Ω arm with an error of 0.0933					
F_0	F_1	F_2	F_3	F_4	F_5
-0.0612	-0.1088	-0.2002	-0.5154	-0.5154	0.0056
F_6	F_7	F_8	F_9	F_{10}	
-0.0068	0.3482	0.0657	0.0925	0.1230	
112.825 Ω arm with an error of 0.113					
F_0	F_1	F_2	F_3	F_4	F_5
-0.0899	-0.1122	-0.2058	-0.5181	0.2468	0.0010
F_6	F_7	F_8	F_9	F_{10}	
-0.0177	0.3675	0.0735	0.0791	0.1757	
55.344 Ω transformer with an error of 0.0264					
F_0	F_1	F_2	F_3	F_4	F_5
0.1033	0.1244	0.1737	0.5030	-0.4465	-0.2272
F_6	F_7	F_8	F_9	F_{10}	
-0.0246	0.0016	-0.0745	-0.1159	-0.0172	
61.8 Ω transformer with an error of 0.0542					
F_0	F_1	F_2	F_3	F_4	F_5
0.1034	0.0977	0.2111	0.4251	-0.5364	-0.0603
F_6	F_7	F_8	F_9	F_{10}	F_6
-0.0995	0.0745	-0.1140	-0.0376	-0.0639	-0.0995

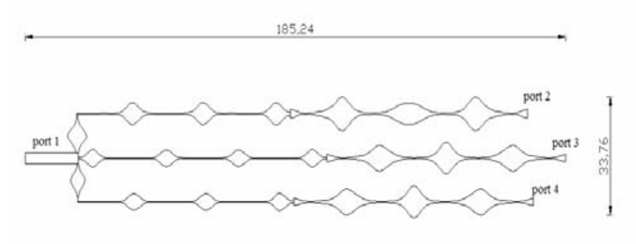
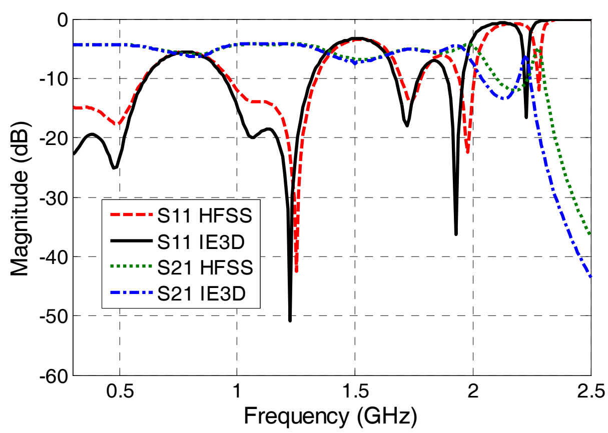


Fig. 3 – Layout of the designed NTL-based WPD
(dimensions are in mm).

From Fig. 4, it can be seen that there is a slight shift in the design frequencies. This shift could be due to the discontinuity effects and the coupling between the adjacent sections. The input port matching parameter (S_{11}), the isolation parameters (S_{23}, S_{24}, and S_{34}), and the output ports matching parameters (S_{22}, S_{33}, and S_{44}) are less than –20 dB at the design frequencies. The transmission parameters (S_{21}, S_{31}, and S_{41}) are around their theoretical values at the design frequencies. Table 3 summarizes the obtained values for the scattering parameters at the design frequencies. The slight discrepancy between HFSS and IE3D results is due to the fact that each simulator uses different technique in simulating the structures.



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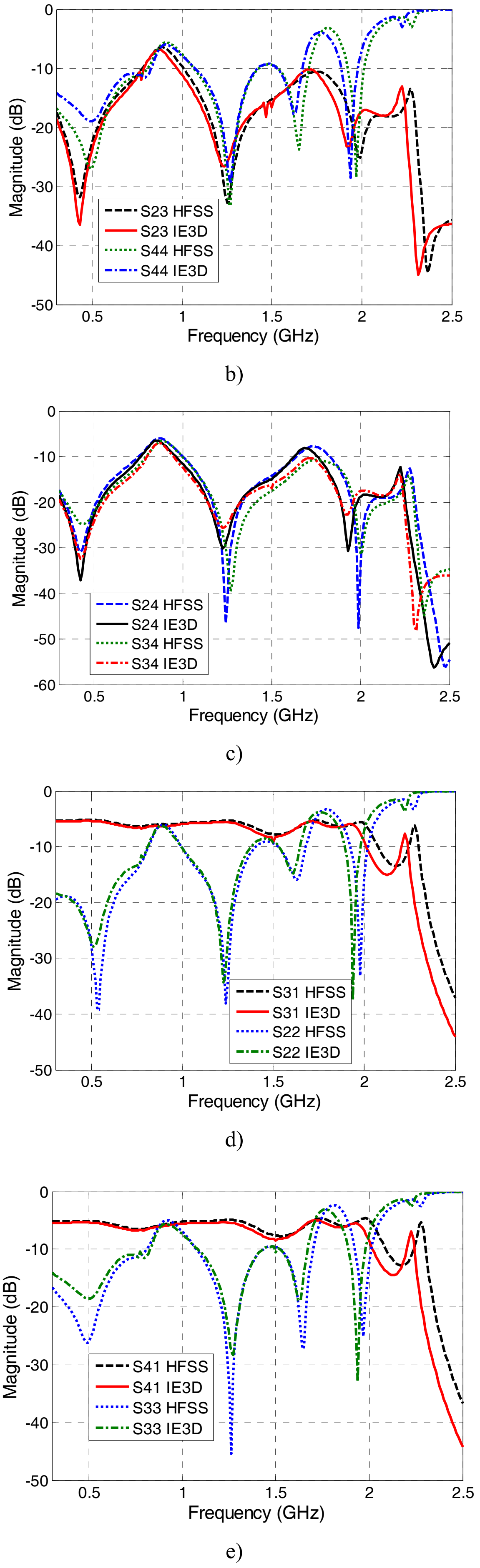


Fig. 4 – Simulated S-parameters for the three-way, non-planar, NTL-based WPD.

Planar three-way WPD can be achieved using two resistors instead of three resistors, as shown in Fig. 5. The first resistor (R_1) is mounted between the ends of arms 1 and 2; while the second resistor (R_2) is mounted between the ends of arms 2 and 3. As before, the values of these resistors are obtained using the built-in optimization engine of the Ansoft Designer circuit model simulator. The values of these resistors are found to be R_1=167.2 Ω and R_2=148.5 Ω. The simulated *S*-parameters of this planar, three-way, NTL-based WPD are shown in Fig. 6.

Table 3

Three-way, NTL-based WPD simulated S-parameters

S-parameters (dB)	S_{11}	S_{21}	S_{31}	S_{41}	S_{22}
HFSS at 0.49 GHz	-18	-4.35	-5.2	-5.1	-26
IE3D at 0.47 GHz	-25.0	-4.36	-5.38	-5.35	-25
	S_{23}	S_{24}	S_{33}	S_{34}	S_{44}
HFSS at 0.49 GHz	-23.6	-22.2	-26.2	-22.7	-27.0
IE3D at 0.47 GHz	-26.8	-25.6	-18.4	-26.7	-18.7
	S_{11}	S_{21}	S_{31}	S_{41}	S_{22}
HFSS at 1.25 GHz	-42.5	-4.2	-5.35	-5	-33.3
IE3D at 1.22 GHz	-50.8	-4.26	-5.6	-5.36	-34.3
	S_{23}	S_{24}	S_{33}	S_{34}	S_{44}
HFSS at 1.25 GHz	-32.8	-42.2	-34.4	-32.8	-28.7
IE3D at 1.22 GHz	-26.5	-30.1	-20	-25.6	-19.8
	S_{11}	S_{21}	S_{31}	S_{41}	S_{22}
HFSS at 1.98 GHz	-22.5	-4.35	-5.56	-4.7	-33.1
IE3D at 1.93 GHz	-36.2	-4.5	-5.93	-5.5	-20.2
	S_{23}	S_{24}	S_{33}	S_{34}	S_{44}
HFSS at 1.98 GHz	-24.9	-31.5	-19.4	-24.4	-22.1
IE3D at 1.93 GHz	-23.5	-30.7	-23.7	-22.7	-24.7
Theoretical values at the three design frequencies	S_{11}	S_{21}	S_{31}	S_{41}	S_{22}
	$-\infty$	-3.98	-5.23	-5.23	$-\infty$
	S_{23}	S_{24}	S_{33}	S_{34}	S_{44}
	$-\infty$	$-\infty$	$-\infty$	$-\infty$	$-\infty$

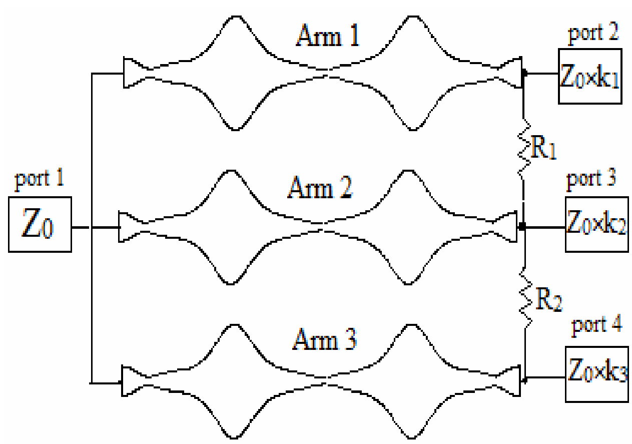
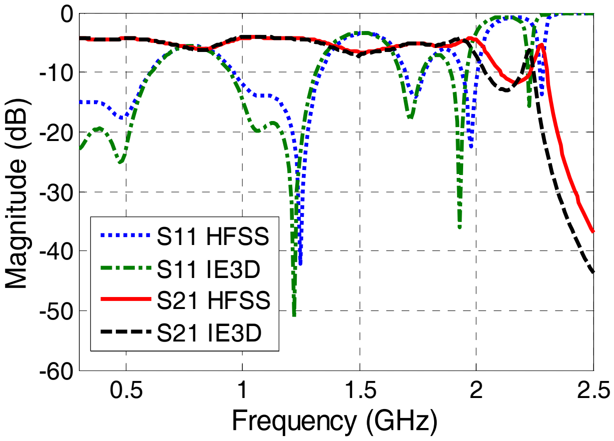


Fig. 5 –Configuration of the planar 3-way WPD.

The simulated *S*-parameters of the planar three-way WPD are in good agreement with the non-planar ones except the isolation between ports 2 and 4. The non-planar design had an S_{24} less than –20 dB at the 3 design frequencies, while it is around –14 dB in the planar structure.



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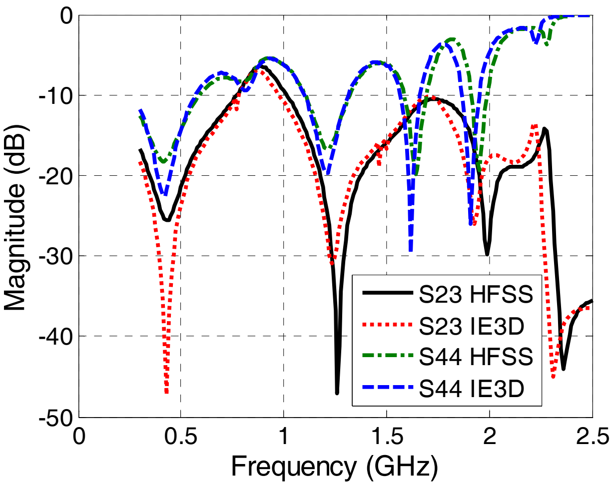

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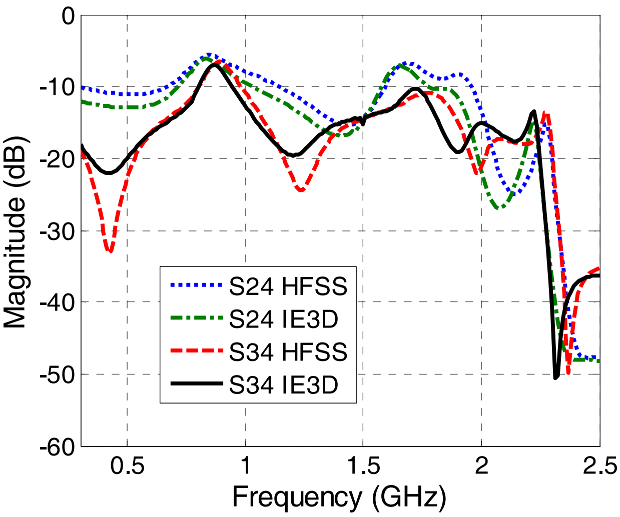

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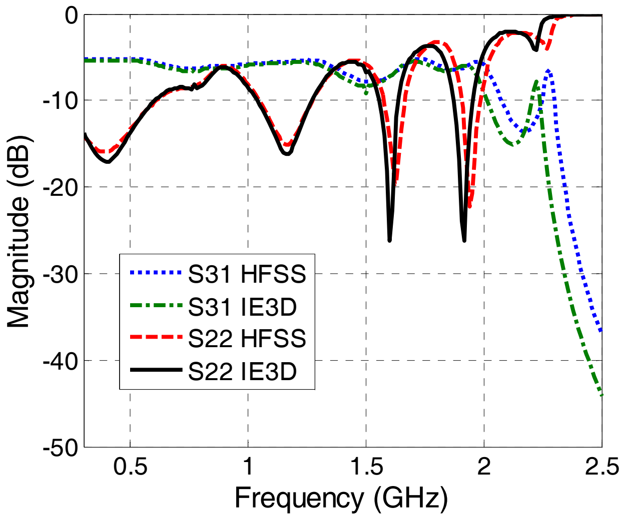

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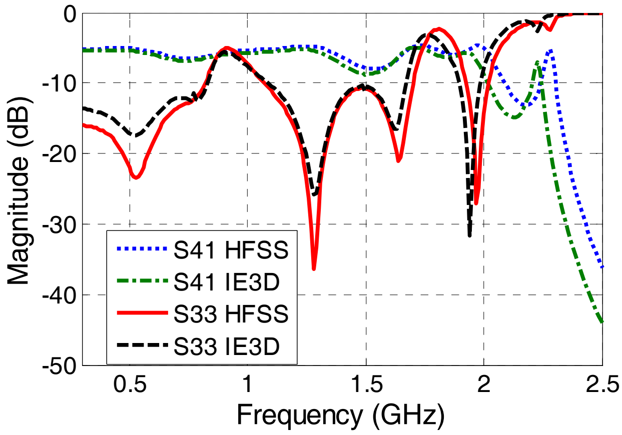

e)

Fig. 6 – Planar three-way NTL-based WPD simulated S-parameters.

4. CONCLUSIONS

In this paper, a 3-way triple band unequal split NTL-based WPD was proposed, where non-uniform transmission line transformers are incorporated to achieve both multi-frequency characteristics and compactness. Both non-planar and planar configurations were designed. The proposed dividers were designed to operate in three bands 0.5 GHz, 1.25 GHz, and 2.0 GHz. In addition to the three NTL-based main arms, three NTL-based output matching transformers were designed to match the output ports to the 50 Ω connectors. Isolation between the output ports was accomplished using several resistors mounted in non-planar and planar modes between adjacent arms. Optimization process was carried out to find the optimal values of these resistors. Simulated *S*-parameters are in good agreement with theoretical ones, which validates the design procedure.

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